Surface Compaction Estimates and Soil Sensitivity in Aspen Stands of the Great Lakes States

Aaron Steber, Ken Brooks, Charles H. Perry, and Randy Kolka

ABSTRACT

Aspen forests in the Great Lakes States support much of the regional timber industry. Management-induced soil compaction is a concern because it affects forest health and productivity and soil erosion. Soil compaction increases bulk density and soil strength and can also decrease air and water movement into and through the soil profile. Currently, most inventories, and specifically the Forest Inventory and Analysis program, use qualitative estimates of soil compaction. This study compared qualitative estimates with quantitative measurements on aspen clearcuts in five national forests in the Great Lakes States. Research sites were stratified into classes of high and low potential for soil compaction on the basis of soil texture. Qualitative visual assessments of compaction were made according to Forest Inventory and Analysis (FIA) phase 3 protocols and compared with physical measurements of bulk density, soil compression strength, and saturated hydraulic conductivity. No differences in compaction between high- and low-risk soils were detected using visual assessments, but quantitative measurements in high-risk, fine-textured soils indicated greater compaction than low-risk, coarse-textured soils. These results illustrate shortcomings in qualitative estimates of compaction made according to FIA phase 3 field protocols. Inexpensive quantitative measurements, such as those taken with a pocket penetrometer, may be sufficient to quantify compaction levels within the plots.

Keywords: soil compaction, aspen clearcut, visual assessment, forest inventory, pocket penetrometer

Aspen acreage has declined in the Great Lakes States over the past 70 years, yet aspen-birch forests remain the second most prevalent forest type in the Great Lakes States behind northern (maple-beech-birch) hardwoods (Cleland et al. 2001). Aspen-birch forests represent 26% of the region's 49.0 million ac of timberland and 25% of the region's 51.9 million ac of forestland (Cleland et al. 2001). In 2002, aspen was the dominant species harvested for pulpwood in the Great Lakes States: it accounted for 3.8 million cords, or 40% of the total roundwood harvested (Piva 2005).

The effects of forest harvesting on soil compaction is of interest because of its consequences for forest health, production, and soil erosion. Soil can become compacted from harvesting equipment caused by ground pressure, machine speed, and wheel slippage (Murphy 1982). Compaction of a given soil is the result of external forces applied to the soil and internal soil characteristics such as particle-size distribution, organic matter content, and soil moisture (Howard et al. 1981, Sheppard 1993, Williamson and Neilsen 2000). Soil compaction increases bulk density and soil strength while breaking down soil aggregates and increasing surface runoff, erosion, and waterlogging (Greacen and Sands 1980, McNabb et al. 2001). Soil compaction can also decrease air movement into and through the soil profile by decreasing pore space and continuity, therefore reducing infiltration capacity and tree root growth (Greacen and Sands 1980, Thompson et al. 1987, McNabb et al. 2001). Accurately assessing the extent and degree of compaction of forest soils is of increasing concern to government, industry, and the public.

In 1928, Congress passed the McSweeny-McNary Act, leading to the creation of the Forest Inventory and Analysis (FIA) program of the US Forest Service (Miles 2002). The FIA program is responsible for conducting inventories to determine the extent and condition of the nation's forest resource. The sampling design includes three phases implemented across all forested lands in the United States (Bechtold and Patterson 2005). In phase 1, millions of points are evaluated by aerial photography and digital orthophotoquads to determine the location and extent of forested lands. These data are then stratified into land cover classifications using satellite imagery and other remotely sensed data (Bechtold and Patterson 2005). During phase 2, crews visit plot locations and collect data on landownership, forest type, tree species, tree size, tree condition, and site attributes, with one phase 2 plot for approximately every 2,425 ha of forested land. Phase 3 plots represent a subset of phase 2 plots, approximately 7,800 plots nationally, representing approximately 38,850 ha each (Bechtold and Patterson 2005). A broader range of forest health attributes are measured on phase 3 plots, including qualitative estimates of soil compaction (US Forest Service 2004). States have the option of increasing the intensity of field measurements by paying for the cost of the intensification (Miles 2002).

Each FIA plot consists of four subplots with three 7.3-m-radius subplots arranged in a triangular pattern around a central subplot. Subplot centers are located 36.6 m apart, with subplots 2, 3, and 4 oriented at 120° angles around the plot center. Each subplot is

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surrounded by an 18-m-radius annular plot that is used for destructive sampling, including the collection of soil samples for laboratory analysis (Bechtold and Patterson 2005). An ocular assessment of percentage of bare soil and percentage of forest showing visual evidence of compaction is made on all four subplots (US Forest Service 2004, O'Neill et al. 2005); the percentage of the subplot that exhibits evidence of compaction is assessed relative to conditions of adjacent undisturbed soil.

No quantitative measurements of soil compaction are taken within any of the four FIA subplots. This may pose a problem in compaction estimation, especially because the disturbance of surface soil by modern heavy machinery is sometimes strikingly obvious, but chronic changes in soil structure due to traffic are not necessarily so obvious and might have more serious and lasting consequences (Greacen and Sands 1980). Although some visual soil disturbances are obviously related to static and dynamic soil properties, visual assessments alone should not be considered an accurate index of changes in soil productivity and hydrologic function (Aust et al. 1998).

Soil compaction can impede the growth of roots and alter the water-holding capacity of soils. Medium- and fine-textured soils throughout the Great Lakes States region are frequently underlain by a fragipan, resulting in perched water whenever soil water recharge exceeds evapotranspiration. The saturated horizons above the fragipan make them particularly susceptible to rutting and root damage (Stone 2002). Compaction generally reduces the available water-holding capacity of fine-textured soils, but it can reduce the size of very large pores and increase water retention in coarse-textured soils (Cullen et al. 1991). Brais (2001) found improved growth on coarse-textured soils in skid trails over adjacent undisturbed areas due to decreases in competition, and concomitant increases in tree predawn water potential. Results from 42 experimental locations representing 25 replicated studies within the North American Long-Term Soil Productivity (LTSP) program found that some higher-porosity soils showed improved root/soil contact, available water holding-capacity, thermal regimes, and/or nutrient uptake after compaction following forest floor removal. However, compaction on finer-textured soils in the LTSP program increased surface drying from forest floor removal and reduced porosity and water-holding capacity while producing excessive soil strength during the growing season (Fleming et al. 2006).

Objective

Currently, most inventory methods, including those implemented in the FIA program, rely on qualitative estimates of soil disturbance and compaction. The objectives of this study are to compare qualitative observations of compaction used in the FIA program with quantitative measurements to determine (1) whether there is a difference in susceptibility to compaction between soils grouped by texture into high-risk potential for compaction (fine-textured soils) and low-risk potential for compaction (coarse-textured soils), and (2) whether the FIA visual method of determining compaction on phase 3 research plots accurately assesses the degree of compaction evident within the plots.

Methods

Ranger District representatives in the Chequamegon-Nicolet, Huron-Manistee, Ottawa, Chippewa, and Superior National Forests identified clearcuts in predominantly aspen stands (*Populus grandidentata*, *Populus tremuloides*) harvested after 1999. Dominant Great Lakes soil types were stratified into regions of high and low potential for soil compaction on the basis of soil texture. Low-risk sites consisted of sands, loamy sands, and sandy loams, whereas high-risk sites consisted of clays, silts, and loams (Table 1). This classification was chosen as a convenient two-category system that could be used by professionals in the field and was used in selection of recently harvested aspen clearcuts based on the textural class of the soil (McNabb 1993, Brais 2001, Fleming et al. 2006). Three clearcuts on high-risk soils and three clearcuts on low-risk soils were chosen randomly in each National Forest; control plots were identified in undisturbed forested areas adjacent to the selected clearcuts. The Huron-Manistee National Forest contained only low-risk plots because of a lack of aspen clearcuts on fine-textured soils.

In each aspen clearcut, 10 areas with visual evidence of compaction consistent with FIA phase 3 protocols were identified, with one of 10 chosen randomly to produce a sampling plot. Visual evidence of compaction is currently assessed by FIA phase 3 crews relative to the condition of nearby undisturbed soils, and a percentage of each plot exhibiting compaction is recorded. Compaction, when present, is also placed into one of three categories (US Forest Service 2004), which include: rutted trail (ruts must be at least 5.1 cm deep into mineral soil or 15.2 cm deep from the undisturbed forest litter surface), compacted trail (resulting from many passes of heavy machinery, vehicles, or large animals), or compacted area (including the junction areas of skid trails, landing areas, work areas, animal bedding areas, heavily grazed areas, etc.). For this study, ten areas with visual evidence of compaction consistent with FIA phase 3 protocols were identified in each aspen clearcut with one of ten chosen randomly to produce a sampling plot.

Although not actual phase 3 plots, these sites are representative of the types of compaction frequently encountered on FIA plots. Sampling plots were established by creating a circle with a 7.3-m radius, equal to FIA subplots, around a center stake in an area that showed visual evidence of compaction. Once the sampling plot was established, the percentage of the plot showing one of the three types of compaction described above was visually determined relative to the condition of nearby undisturbed soils consistent with FIA phase 3 protocols (US Forest Service 2004).

Inside each sampling plot, five azimuths and distances were randomly measured from a center stake and used to locate points for physical measurements. The same plot design was also used in control plots within undisturbed forest stands. Control plots were located adjacent to each selected clearcut plot, where selection was based on similarity in the soils, landscape position, and vegetation. In each clearcut plot and undisturbed plot, the organic forest floor layer was removed at the end of each azimuth. Quantitative measurements, including surface soil compression strength, bulk density, resistance to penetration, and saturated hydraulic conductivity, were recorded.

A CL-700 pocket penetrometer from ELE International was used to measure surface soil compression strength. The tip of the penetrometer was inserted into the soil to a groove located 6 mm from the tip. If coarse fragments prevented penetration to a depth of 6 mm, no measurement was recorded, and another insertion was made in the same general area until a depth of 6 mm was reached. A red ring on the barrel of the penetrometer was then read directly in kg/cm^2 to obtain the measurement. In extremely soft soil, a CL-701 adapter foot was connected to the pocket penetrometer, increasing the effective area of the piston 16 times. Measurements read with the

Table 1. Location of research plots.

Plot	Soil type	Risk	Location	County
Chequamegon-Nicolet, WI				
1	Silt loam	High	T. 40 N, R. 2 E. sec. 1	Price
2	Loam	High	T. 44 N, R. 7 W, sec. 34	Bayfield
3	Loam	High	T. 43 N, R. 3 W, sec. 22	Ashland
4	Sandy loam	Low	T. 41 N, R. 5 W, sec. 24	Sawyer
5	Sandy loam	Low	T. 32 N, R. 14 E, sec. 20	Oconto
6	Sandy loam	Low	T. 41 N, R0.11 E, sec. 13	Vilas
Huron-Manistee, MI				
1	Sand	Low	T. 25 N R. 4 E, sec. 10	Oscoada
2	Sand	Low	T. 28 N R. 9 E, sec. 28	Alcona
3	Sand	Low	T. 26 N R. 7 E. sec. 8	Alcona
Ottawa, MI				
1	Sand	Low	T. 49 N R. 35 W, sec. 36	Baraga
2	Sandy loam	Low	T. 48 N R. 36 W, sec. 19	Houghton
3	Clay	High	T. 49 N R. 40 W, sec. 35	Ontonagon
4	Clay	High	T. 49 N R. 40 W, sec. 3	Ontonagon
5	Clay loam	High	T. 49 N R. 40 W, sec. 34	Ontonagon
6	Sandy loam	Low	T. 48 N R. 36 W, sec. 19	Houghton
Chippewa, MN				
1	Clay loam	High	T. 147 N R. 27 W, sec. 35	Itasca
2	Silt loam	High	T. 57 N R. 26 W, sec. 6	Itasca
3	Sandy loam	Low	T. 148 N R. 30 W, sec. 14	Beltrami
4	Clay loam	High	T. 141 N R. 31 W, sec. 7	Cass
5	Sandy loam	Low	T. 141 N R. 31 W, sec. 27	Cass
6	Sandy loam	Low	T. 142 N, R. 26 W, sec. 8	Cass
Superior, MN				
1	Gravel loam	Low	T. 63 N R. 1 W, sec. 34	Cook
2	Silt loam	High	T. 56 N R. 13 W, sec. 24	St. Louis
3	Sandy loam	Low	T. 56 N R. 13 W, sec. 8	St. Louis
4	Sandy loam	Low	T. 60 N R. 11 W, sec. 9	Lake
5	Silt loam	High	T. 60 N R. 11 W, sec. 9	Lake
6	Silt loam	High	T. 63 N R. 11 W, sec. 9	Lake

adapter foot were divided by 16 to get the surface soil compression strength of the test material. Each measurement was converted from kg/cm^2 to kilopascals. In each plot, three insertions to a depth of 6 mm were made at the end of each azimuth and averaged to get a representative value for surface soil compression strength. A total of 810 pocket penetrometer measurements were collected.

The soil core method was used to collect bulk density measurements. Samples were collected using an impact-driven soil corer from AMS, Inc., with two 5-cm-diameter × 10-cm-long stainless steel soil core liners. Samples were collected from 0 to 10 cm and 10 to 20 cm at the end of each azimuth, for a total of 10 samples per plot. Samples were immediately placed in air-tight soil tins and taped to prevent evaporative losses. Each sample was weighed, dried in an oven at 105°C for 24 hours, and weighed again to determine bulk density. Extremely thick clay and rocky soils prevented sampling in a few plots, so no bulk density samples were taken at the depth of restriction. A total of 440 bulk density samples were collected.

The soil's resistance to penetration was measured with a Rimik CP-20 cone penetrometer from Rimik Agricultural Electronics. This instrument has a cone diameter of 1.27 cm, a cone angle of 30°, and a cone surface area of 1.27 cm^2 (Rimik Agricultural Electronics 1994). The cone penetrometer was calibrated before use at the US Forest Service Northern Research Station in Grand Rapids, Minnesota. At the end of each of the five azimuths, three probe insertions were collected, for a total of 15 insertions per plot. Soil strength was measured in kilopascals at 2-cm intervals, from 0 to 50 cm, at an insertion rate of 2 m per minute. A total of 16,345 measurements were recorded.

A compact constant head permeameter (Amoozemeter) from Ksat, Inc., was chosen to determine saturated hydraulic conductivity in the field. This permeameter uses a constant-head well permeameter technique (also known as the shallow-well pump-in technique). Measurements of saturated hydraulic conductivity were taken at the end of the first and third azimuth at each plot. The steady-state rate of water flow into the soil was measured while the level of water in the hole remained constant; saturated hydraulic conductivity was calculated by the Glover solution (Amoozegar 1989). Extremely rocky soils in the Superior National Forest precluded the use of the constant head permeameter because of hole irregularity.

One-way analysis of variance (ANOVA) was used to compare the mean of each category of measurements. Analyses were completed in R, an open-source statistical software program regarded as an implementation of the S language (Crawley 2002). Post-ANOVA multiple comparisons were made using Tukey's "honestly significant difference" test at a 95% family-wise confidence interval.

Results and Discussion

Although qualitative visual assessments of compaction between high- and low-risk soil categories were not different, there were differences in the quantitative assessments between the two groups (Table 2). Surface soil compression strength measured with a pocket penetrometer in clearcut areas was greater in high-risk plots than in low-risk plots. No difference was found between high- and low-risk soils in adjacent undisturbed plots. Soil compression strength measurements also differed between high- and low-risk plots in clearcuts and their respective adjacent undisturbed plots. These results confirmed the effectiveness of pocket penetrometers for distinguishing between compacted and uncompacted areas (Amacher and O'Neill 2004a).

Bulk density measurements at the 0–10-cm depth were greater on high-risk soil plots than low-risk soil plots in clearcut areas. There

Table 2. A comparison of plot condition group means based on soil risk level.

	Aspen clearcuts		Undisturbed stands	
	High	Low	High	Low
Visual assessment of compaction (%)	63[a]	66[a]		
Surface soil strength (kPa)	232[a]	165[b]	36.7[c]	30.1[c]
Bulk density 0–10 cm (g/cm^3)	1.65[a]	1.45[b]	1.25[c]	1.15[c]
Bulk density 10–20 cm (g/cm^3)	1.64[a]	1.53[a]	1.41[b]	1.39[b]
Saturated hydraulic conductivity (m/day)	2.88[a]	19.1[b]	8.72[a,b]	51.2[c]

In each row, values followed by different letters are significantly different at $\alpha = 0.05$.

were no differences in bulk density at the 0–10-cm depth between high- and low-risk soils in the undisturbed forest stands adjacent to the clearcut areas. Bulk densities at the 0–10-cm depth are representative of surface mineral horizons of forest soils, which are sensitive to heavy equipment traffic because of characteristically high total porosities and low internal shear strengths (Lenhard 1986). As part of the LTSP study, Stone and Elioff (1998) compared five noncompacted plots to four compacted plots and found that compaction significantly increased bulk density at each 10-cm depth increment of a 30-cm sample, with the greatest change in the surface 10 cm. In this study, no differences were found between high- and low-risk soils at the 10–20-cm depth, yet the bulk density of samples 10–20-cm depth was greater than those from adjacent undisturbed stands.

Under the action of a penetrometer, the soil yields in local shear failure and must be compressed to accommodate the volume of the penetrometer (Greacen and Sands 1980). This is similar to the energy root tips need to expend to penetrate the soil medium. If more energy is required by the roots to penetrate the soil, less energy will be available for the plant to grow larger (Landsberg et al. 2003). Resistance to penetration (soil strength) from 0 to 20 cm measured with a cone penetrometer was greater in high-risk plots in clearcuts than in low-risk plots in clearcuts (Figure 1). The same pattern was observed in undisturbed forested stands; soil strength was greater in high-risk plots than in low-risk plots. High-risk plots in clearcuts also had lower saturated hydraulic conductivities than low-risk plots, but high-risk undisturbed stands had lower saturated hydraulic conductivities than low-risk undisturbed stands as well. Estimates of saturated hydraulic conductivity were very closely tied to the texture of the soil being studied, reflecting the fact that hydraulic properties of soils are, in part, a function of their texture and structure.

Forest harvesting is likely to have greater impacts on soil properties, stand composition, and future site productivity than any other activity during the rotation. The size, weight, and power of logging equipment have increased greatly during the last 25 years, and its misuse can degrade sites in a short time (Stone 2002). The results of this study suggest that special consideration should be given to harvesting aspen stands on fine-textured soils, especially when soils are wet. Fine-textured soils hold more water than coarse-textured soils because of surface tension. Soil is most easily compacted when wet or moist, and the susceptibility of a soil to compaction decreases at lower soil water contents (McNabb 1993). Stone (2002) argues that wet riparian areas, and poorly drained inclusions, should be delineated on the ground during sale preparation and excluded from the cutting unit boundaries. Care must be taken especially in susceptible areas to limit compaction and its effects on forest productivity. Stone and Elioff (1998) compared five noncompacted plots to four compacted plots and found that neither bulk density nor soil strength showed any trend toward recovery to pretreatment conditions after 5 years. Corns and Maynard (1998) estimated that bulk densities could take up to 21 years to recover from harvests in Alberta.

We poststratified the data to compare the visually assessed types of compaction found within each plot independently of soil risk level. Qualitative visual assessments of compaction were compared across the three categories of compaction assessed in the 2004 FIA phase 3 Field Guide (compacted area, compacted trail, and rutted trail) (US Forest Service, 2004). Compacted areas had a mean percentage of compaction that was greater than in clearcuts with compacted trails and rutted trails (Table 3). The compacted trails and rutted trails in clearcuts were not significantly different from each other. Surface soil compression strength measurements showed no differences among the three types of compaction, although they were all greater than those of adjacent undisturbed plots. Importantly, some quantitative measurements captured significant differences opposite those found qualitatively. The mean bulk density at 0–10 cm of compacted areas was actually lower than the mean bulk density at that depth in compacted trails and rutted trails, even though visual assessments determined that compaction was higher in compacted areas than compacted trails and rutted trails. In short, although compacted areas looked the most compacted, they were actually affected the least.

These findings suggest a potential problem with strictly qualitative visual assessments of compaction. Qualitative assessments of compaction in FIA phase 3 plots based solely on visual characteristics may not be consistent with the degree of compaction exhibited in the plots. In a similar study, Aust et al. (1998) categorized different harvested sites in South Carolina into five classes of visual disturbance to assess compaction. Quantitative measurements including bulk density, saturated hydraulic conductivity, and pore space proved that spatial disturbance was not synonymous with damage (Aust et al. 1998). There are many factors that could contribute to this inconsistency. By using a visual estimate, any compaction evident in the plot that is covered by vegetation is inherently underrepresented. This could cause problems for field crews, especially

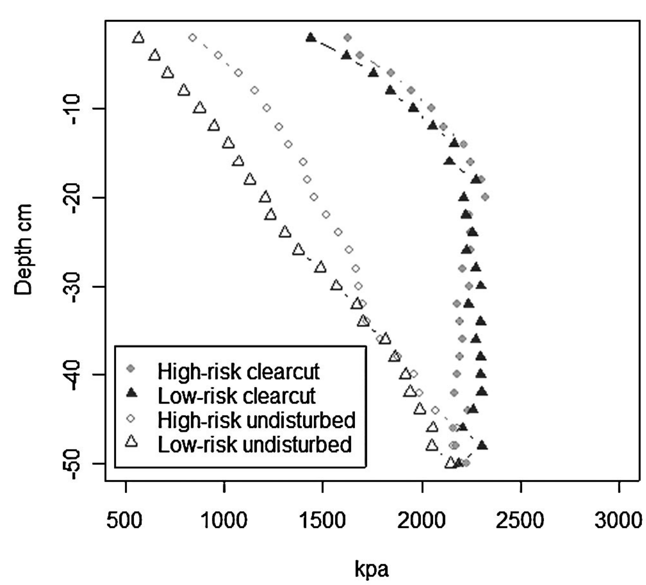

Figure 1. Cone penetrometer data by soil risk level. Resistance to penetration of forest soils in the Upper Midwest from 0 to 50 cm by soil risk level.

Table 3. A comparison of plot condition group means based on type of compaction evident independent of soil texture. CA, compacted area; CT, compacted trail; RT, rutted trail.

	Aspen clearcuts			Undisturbed stands*		
	CA	CT	RT	CA	CT	RT
Visual assessment of compaction (%)	75^{a}	55^{b}	62^{b}			
Surface soil strength (kPa)	187^{a}	209^{a}	192^{a}	26.2^{b}	37.6^{b}	36.6^{b}
Bulk density 0–10 cm (g/cm^3)	1.36^{a}	1.59^{b}	1.65^{b}	1.09^{c}	1.23^{c}	1.26^{c}
Bulk density 10–20 cm (g/cm^3)	1.51^{a,b}	1.65^{a}	1.57^{a,b}	1.38^{b}	1.42^{b}	1.40^{b}

In each row, values followed by different letters are significantly different at $\alpha = 0.05$.
* Undisturbed plots with no visual evidence of compaction located adjacent to harvested plots with compaction evident.

later in the year, when vegetation is abundant. Subsurface compaction also may be underrepresented if it exists without showing the visual attributes consistent with FIA field protocols.

The purpose of the soil indicator in the FIA program is to quantify the extent of human-induced changes to the physical properties of forested soils that are of sufficient magnitude to adversely affect soil fertility, hydrology, and/or other ecosystem processes or cause significant reductions in productivity (Amacher and O'Neill 2004b). However, visual assessments do not quantify the degree to which areas inside phase 3 plots may be affected. Bulk density measurements are taken as an index of potential problems, but they are taken in destructive sampling locations outside of the phase 3 plots, which does not allow for the compaction existing within the plots to be assessed.

One method of assessing within-plot compaction would be the addition of pocket penetrometers to the FIA phase 3 program. Any method selected to measure the degree of soil compaction must be fast and easy to implement because of time and resource constraints in collecting phase 3 data (Amacher and O'Neill 2004a). Pocket penetrometers meet these needs, allowing for multiple measurements to be taken with relative ease. Pocket penetrometers can detect significant differences between compacted areas and their associated undisturbed areas, and between compacted trails and undisturbed areas (Amacher and O'Neill 2004a). For example, field crews could apply a grid over a selected area (Figure 2) and randomly choose squares within this grid to collect penetrometer readings.

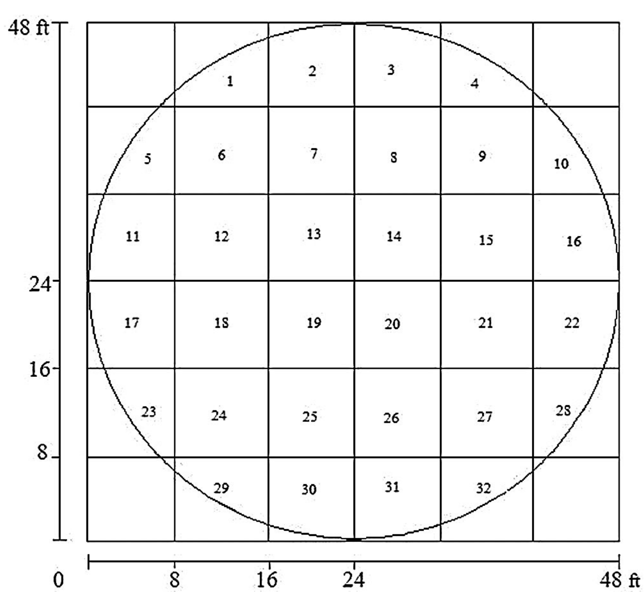

Figure 2. Sampling grid used to determine site of pocket penetrometer measurements in each plot.

This ability to determine detectible differences between compacted and uncompacted soils permits a quantitative measurement of compaction to coincide with visual assessments made within the phase 3 plots.

Conclusions

No differences in compaction between high-risk and low-risk soils were detected using visual assessments. Low-risk, coarse-textured soils have less total pore space than fine-textured soils and in general would tend to have higher bulk densities. However, bulk density measurements from 0–10 cm and surface soil compression strength measurements made with a pocket penetrometer were greater in clearcuts on high-risk fine-textured soils than in low-risk, coarse-textured soils, with no differences found between their adjacent undisturbed stands.

Visual assessments made by forest managers on harvested soils may not adequately measure soil compaction. The results of this study suggest that quantitative measurements taken with a pocket penetrometer could be a valuable tool for foresters in their postharvest evaluations. Foresters could apply a grid over a selected area and randomly choose squares within this grid to collect penetrometer readings. Pocket penetrometers at the very least can be used as a tool to quantify areas that foresters visually identify as compacted compared with undisturbed areas, and just having the tool in their pocket will hopefully increase their recognition and understanding of the effects of soil compaction on future productivity.

When data from the plots were grouped by the type of compaction, visual assessments overestimated compaction as determined from quantitative data. These results show that the FIA method of using a qualitative visual assessment of compaction on phase 3 plots is not accurate. The use of a pocket penetrometer would improve the assessment of compaction on FIA phase 3 plots by physically measuring the degree of compaction within a plot. Using randomly selected points from a grid overlying the plot to take pocket penetrometer measurements to better quantify the extent of compaction evident within the plot is recommended. Continual effort involving the development and refinement of measurements taken to detect and report levels of compaction as part of the FIA program is essential to accurately and efficiently assess the state of forested soils in the United States.

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